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Research paper

Production of subsurface drip-irrigated okra under different lateral spacings and irrigation frequencies

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In this study, an experiment was conducted to investigate the optimum lateral spacing and irrigation frequency for subsurface drip irrigated okra in the semi-arid region of Haryana (India). Two lateral spacings (45 cm and 60 cm) and four irrigation frequencies (daily, after 1, 2 and 3 days) were selected to grow okra in the Kharif season of 2019 and 2020. The effect on soil water dynamics, growth parameters, efficiency and yield were assessed using equal amounts of water under all the treatments on the basis of pan evaporation. The results from the study depict that the overall soil moisture decreased laterally, but increased vertically downward with the increase in the irrigation interval. On the basis of soil water dynamics, plant growth parameters, efficiency and yield of okra, it was concluded that subsurface drip irrigation with daily irrigation at 45 cm lateral spacing gives better performance than all other treatments in sandy loam soil. The present study highlights the significance of proper irrigation frequency and lateral spacing for maximum production of okra. Using these guidelines, the income of okra growers/farmers in the semi-arid region may be increased by choosing the best frequency and lateral spacing of subsurface drip irrigation.

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INTRODUCTION

Okra or lady finger (*Abelmoschus esculentus* L.) is grown mostly in tropical and subtropical regions of the world and is a marketable crop grown for trading in many countries, e.g., India, Turkey, Iran, Yugoslavia, Bangladesh, Afghanistan, Pakistan, Burma, Japan, Malaysia, Brazil, Ghana, Ethiopia, Cyprus and the southern United States. It is called Bhindi in the Hindi language and Asra-pattraka in the Sanskrit language. It is used as an edible vegetable which is rich in Vitamin A and low in calories. Dry seed of okra contain 18–20% oil and 20–23% protein and is used for its oil, and protein and as a coffee additive (Berry et al., 1988). All parts of okra are used, and for different purposes: e.g. the foliage can be used as biomass and dry stems are used for paper and as a fuel. Fibres extracted from the stems of okra are used for making strings and nets in some parts of the world. Okra pods are a good source of vitamins, calcium, potassium and other minerals. 100 g of the edible portion of okra contains 1.9 g protein, 0.2 g fat, 6.4 g carbohydrate, 0.7 g minerals and 1.2 g fibre (Gopalan et al., 2007).

In India, farmers are facing very low availability of land and surface irrigation methods are most commonly used for irrigation of vegetable crops (Himanshu et al., 2013). Sustainable management and judicious use of water is the only option available to increase the production with limited water resources, and can only be obtained by modern irrigation methods. Among the modern techniques of irrigation, drip irrigation or trickle irrigation is associated with the enhanced water management technique of irrigating only the root zone of the crop, which results in maximum water use efficiency and crop yield with declining water losses to deep percolation, runoff and soil evaporation. With the use of drip irrigation (surface and subsurface) cultivators can attain both application and water use efficiencies of up to 85% (Thompson et al., 2009). Subsurface drip irrigation saves water by up to 20–25% in comparison to flood irrigation because it applies water below the soil surface in the root zone of the plant through the emitter (Camp, 1998).

Lateral spacing offers the most effective and convenient drip irrigation parameter for management of the wetted region where most of the plant's roots are concentrated (Bozkurt et al., 2006). Okra under subsurface drip irrigation system has been widely studied and showed higher yield (Singh and Rajput, 2007; Patil and Tiwari, 2018; Vadar et al., 2019; Mahmoudi et al., 2020) in comparison to other irrigation methods. Various studies have been conducted to assess the effect of different lateral spacings (Singh et al., 2010; Tejaswini et al., 2021) and irrigation frequencies (Thind et al., 2008; Bahadur et al., 2009; Jayapiratha et al., 2010; Sedara and Sedara, 2020) on okra yield and water use efficiency. Mahanta et al. (2022) studied the effect of saline water on an okra crop using a subsurface drip irrigation system in salt-affected soil in West Bengal, India. The highest yield and water use efficiency was obtained using 2 $dS \cdot m^{-1}$ saline water in comparison to 6 $dS \cdot m^{-1}$, 10 $dS \cdot m^{-1}$ and 14 $dS \cdot m^{-1}$ saline water. Patil and Tiwari (2018) reported a 56.4% higher yield of okra grown in sandy loam soil in India using subsurface drip versus furrow irrigation. Singh and Rajput (2007) recommended that laterals of subsurface drip irrigation should be placed at 10–15 cm depth below the soil surface for higher okra yield in sandy loam soil of New Delhi, India. Mahmoudi et al. (2020) assessed the growth and yield of okra under surface and subsurface drip irrigation in sandy loam soil of Tunisia using treated wastewater and found the highest yield of 4.59 $t \cdot ha^{-1}$ under subsurface drip irrigation was obtained at 5–15 cm emitter depth.

Haryana is one of India's smallest but most developed states and around 65% of its population is located in rural areas which are usually engaged in agriculture and related activities. In spite of being one of the agriculture-dominated states of India, Haryana is a water-deficient state and water availability for irrigation is a big constraint for agricultural production (Khedwal and Chaudhary, 2021). The rainfall in the state is irregular and inconsistent, ranging from approximately 300–1 100 mm (Darshana and Pandey, 2012). The sustainable management and judicious use of water is only option available to increase production with limited water resources, and can only be achieved through modern irrigation methods. In India, okra is grown on 528 000 ha of land with a total production of 6 146 000 metric tons in 2016–17 (Anonymous, 2017). India ranks first in the world in the production of okra, with a 66.3% share (Anonymous, 2017), and the crop has good potential for foreign earnings. The per hectare productivity of okra (11 $t \cdot ha^{-1}$) in India is far above the world average (5.26 $t \cdot ha^{-1}$), though a few countries, e.g. Saudi Arabia (14.43 $t \cdot ha^{-1}$) and Ghana (21 $t \cdot ha^{-1}$) achieve better productivity. In Haryana, the total area under okra cultivation is about 21 420 ha producing 219 020 t. The average productivity of okra in Haryana is about 10.23 $t \cdot ha^{-1}$, lower than many other Indian states (Anonymous, 2017). Drip irrigation enhances the yield of okra up to 14% as compared to conventional surface irrigation methods (Birbal et al., 2013). The effect of lateral spacing, irrigation frequency and soil water distribution for a surface and subsurface drip irrigation system have been studied for okra grown in different soil types in India and abroad. But the behaviour of okra yield under different lateral spacings and irrigation frequencies using subsurface drip irrigation system has not been reported in the literature for the semi-arid region of Haryana (India) where water is a big constraint. It is therefore essential to examine the effect of variable irrigation regimes and lateral spacings in order to obtain the maximum yield, efficiency and economic return from okra using subsurface drip irrigation. The aim of this study was to provide a guideline for okra growers of semi-arid regions to achieve maximum production, with the following specific objectives: (i) to determine the response of soil water dynamics of okra crop grown using subsurface drip irrigation system under different irrigation regimes and lateral spacings, and (ii) to investigate the effect on growth parameters, efficiency and yield of different lateral spacings and irrigation frequencies.

MATERIALS AND METHODS

Study area

This study was carried out at a field of the Department of Soil and Water Engineering, College of Agricultural Engineering and Technology, Chaudhary Charan Singh Haryana Agricultural University (CCS HAU), Hisar, Haryana (India). The location of the study area is 29.14°N and 75.70°E with an altitude of 212 m above mean sea level (Fig. 1). The study area falls within a semi-arid region of subtropical climate and is characterized by hot summers with a maximum temperature of 45°C or higher, and cold winters with a minimum temperature of 1 to 2°C or even lower (Singh et al., 2010). The average annual rainfallis about 459 mm, out of which 80% occurs during the southwest monsoon season (June to September). The soil type is well-drained sandy loam soil composed of 76.40% sand, 6.40% silt and 17.20% clay,

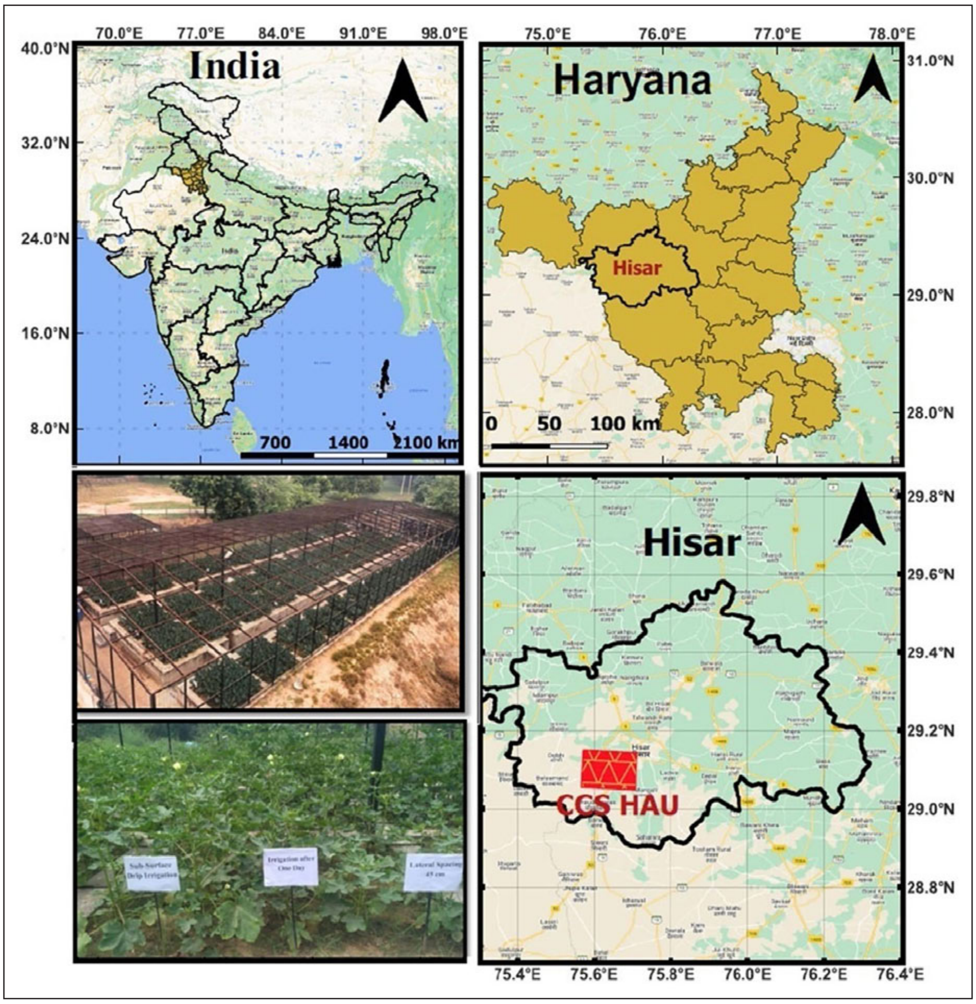

Figure 1. Location of study area

Table 1. Soil properties at the experimental site

Parameter	Soil depth (cm)			
	0–15	15–30	30–45	45–60
Texture	Sandy loam	Sandy loam	Sandy loam	Sandy loam
Sand (%)	75.17	78.18	78.12	78.18
Silt (%)	6.87	5.96	5.76	5.70
Clay (%)	17.96	15.86	15.92	16.12
Bulk density	1.56	1.54	1.58	1.56
pH	8.06	8.05	8.02	8.05
EC1:2	0.25	0.22	0.18	0.19
N (kg·ha^{-1})	118.9	117.5	114.8	119.1
P (kg·ha^{-1})	16.2	18.6	16.6	12.8
K (kg·ha^{-1})	178.3	168.6	156.8	152.5
Organic carbon (%)	0.25	0.29	0.26	0.24
Basic infiltration rate	2.55 cm·h^{-1}			

with pH of 7.64, EC of 0.21 dS·m^{-1} and organic carbon of 0.25% in the upper 0–60 cm depth (calculated/measured in the present study). The average bulk density of soil was 1.55 g·cm^{-3} with basic infiltration rate of 2.55 cm·h^{-1} (Table 1). The field capacity and permanent wilting point in the study area is 24.87 and 7.51%, respectively (Kumar et al., 2021).

Approach

The following methodology was adopted: (i) estimation of irrigation scheduling (i.e. timing and amount of water applied) at daily frequency, or after 1, 2 and 3 days, for okra grown using subsurface drip irrigation system, (ii) determination of soil moisture at different depth and radial distance from dripper using gravimetric method, (iii) calculation of plant growth parameters (i.e. plant height (cm), numbers of pods per plant, yield, irrigation water use efficiency (IWUE) and fertilizer use efficiency (FUE)) at different irrigation frequencies and lateral spacings, and (iv) identification of best frequency and spacing for okra grown under subsurface drip irrigation system to obtain the maximum IWUE, FUE and yield.

Experimental design

The experiment was carried out in the years of 2019–20 and 2020–21 using 2 lateral spacings (45 cm and 60 cm) and 4 irrigation frequencies (daily, after 1, 2 and 3 days) under subsurface drip irrigation. The different treatment combinations along with their designated symbols are shown in Table 2. A square field plot of 2 m × 2 m size (protected with wire mesh to prevent any damage by animals, including birds) with total count of 24 in number and each single trial consist of 3 replicates for statistical analysis and design of the plot was split plot design. The subsurface drip irrigation system laid in the experimental site was fully automated and laterals were laid at 10 cm below the soil surface. The Varsha Uphar variety of okra was selected and seeds were sown at a spacing of 45 cm × 40 cm and 60 cm × 30 cm in the month of June. The field layout of the experiment with 45 and 60 cm lateral spacings is shown in Fig. 2. The standard practices for plant protection, agronomics and fertilization were applied during the cropping season. For the nutritional requirements of okra, 100 kg·ha^{-1} of nitrogen, 60 kg·ha^{-1} of phosphorus and 25 t·ha^{-1} of FYM (farm yard manure) were applied in the experimental field. Monochrotophos and chlorpyriphos were applied to control spotted bollworm, termites, white grub and whiteflies attacking the crop. Seeds were treated with *Trichoderma viride* and sown on 25 June 2019 and 16 June 2020. Fertilizers, i.e., nitrogen, phosphorus and potassium, were applied as per the recommendation given by DEECCSHAU (2017) Recommended doses of nitrogen and phosphorus for okra are 100 and 60 kg·ha^{-1}, respectively, which was applied to the crop. A full dose of phosphorus along with a one-third dose of nitrogen was applied before sowing. The remaining nitrogen fertilizer (two-thirds) was applied through the fertigation unit of drip irrigation.

Irrigation scheduling for okra

Initially, for germination, 5 cm of irrigation was applied through flood irrigation. After germination, irrigation was applied on the basis of 100% pan evaporation (ET_{pan}). An equal amount of water was applied in all treatments. The crop evapotranspiration (ET_c) was calculated by multiplying crop coefficient (K_c, Patil and Tiwari, 2018; Duhan et al., 2021), cumulative pan evaporation and pan coefficient (K_p, US pan evaporation, 0.7). The crop coefficient and duration (days) under different growth stages of okra are shown in Table 3. The volume of water required per plot was calculated using the following formula (Kaulage, 2017):

$$V = \frac{ET_c \times Ls \times Es \times Wa}{EU} \quad (1)$$

where V = volume of water applied (L·day^{-1}·emitter^{-1}), Ls = lateral spacing, Es = emitter spacing, Wa = wetted area factor (0.8 up to 30 DAT and 1.0 after 30 DAT) (Mane and Magar, 2008), EU = emission uniformity of the system (0.90).

Irrigation time was calculated by:

$$\text{Irrigation time (h)} = \frac{V}{q \times \text{no. of drippers per plot}} \quad (2)$$

where q = dripper discharge (L·h^{-1})

The effective rainfall during the experimental period was subtracted from Eq. 1 and the remaining water was applied through the drip irrigation system. After considering both effective rainfall and pan evaporation, the volume of water was calculated using Eq. 1. From drip discharge and volume of water applied, irrigation time was calculated using Eq. 2. In the daily irrigation treatment, water was applied on the basis of the previous day's pan evaporation and for irrigation after 1 day, 2 days and 3 days, cumulative pan evaporation of preceding days was taken into the account.

Table 2. The different treatments of irrigation frequency and lateral spacing

Sr. No.	Treatment	Abbreviation
1	Daily irrigation with 45 cm lateral spacing	I_1L_{45}
2	Irrigation after 1 day with 45 cm lateral spacing	I_2L_{45}
3	Irrigation after 2 days with 45 cm lateral spacing	I_3L_{45}
4	Irrigation after 3 days with 45 cm lateral spacing	I_4L_{45}
5	Daily irrigation with 60 cm lateral spacing	I_1L_{60}
6	Irrigation after 1 day with 60 cm lateral spacing	I_2L_{60}
7	Irrigation after 2 days with 60 cm lateral spacing	I_3L_{60}
8	Irrigation after 3 days with 60 cm lateral spacing	I_4L_{60}

Note: I = irrigation frequency, L = lateral spacing

Table 3. Crop coefficient of okra crop used in the present study

Crop stage	Days after sowing (DAS)	Crop coefficient
Initial stage	0–19	0.51
Vegetative stage	20–27	0.72
Flowering stage	28–47	0.92
Fruiting stage	48–83	0.93
Harvesting stage	84–102	0.53

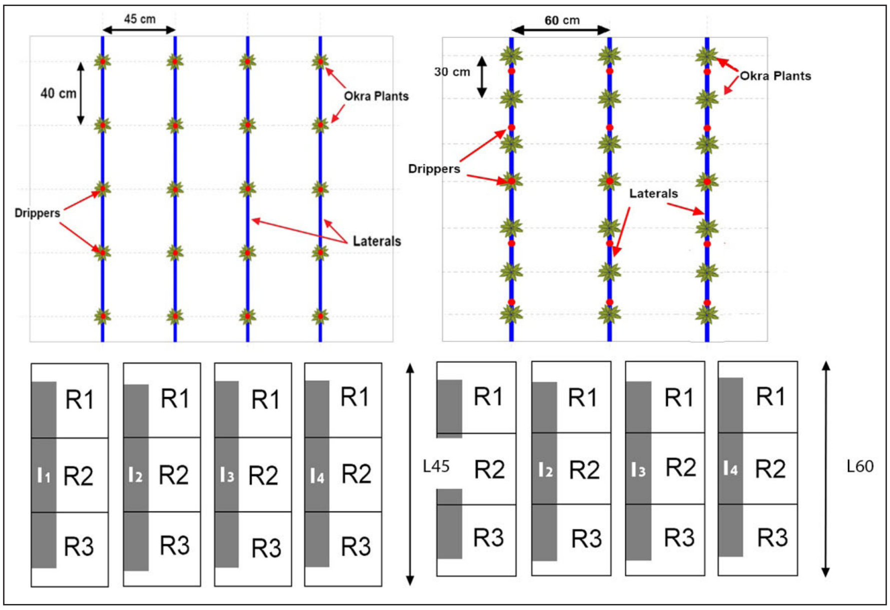

Figure 2. Layout of the experiment with 45 and 60 cm lateral spacing used in the study area

Soil water dynamics and statistical analysis

The soil samples were collected randomly from the field with the help of a tube auger hole (James and Wells, 1990) at different depths (0–15, 15–30, 30–45 and 45–60 cm) from the soil surface in a vertical direction. The samples were also collected radially. At 45 cm lateral spacing, the samples were collected radially at 0, 11.25 and 22.5 cm distance from the dripper, whereas at 60 cm spacing, the samples were collected radially at 0, 15 and 30 cm distance from the dripper. The soil moisture was determined by the gravimetric method (Reynolds, 1970) in which samples were oven-dried for 24 h at 105°C and moisture content determined (Eq. 3).

$$\text{Moisture content (\%)} = \frac{W_1 - W_2}{W_2} \times 100 \tag{3}$$

where W_1 = weight of soil sample before drying (g), W_2 = weight of soil sample after drying (g).

The depth of the water available in the root zone (Michael, 2008) was also calculated using the following equation:

$$d_w = \frac{\rho_s \times \text{moisture content} \times d_s}{\rho_w \times 100} \tag{4}$$

where d_w = depth of water available in the root zone (cm), ρ_s = density of soil (g·cm^{-3}), ρ_w = density of water (g·cm^{-3}), d_s = depth of soil (cm).

Crop growth and yield parameters

Crop parameters like plant height (cm), number of pods per plant, irrigation water use efficiency (kg·m^{-3}), fertilizer use efficiency (kg·kg^{-1}) and total yield (kg·ha^{-1}) were calculated for the different treatments. Plant height (cm) was measured from the base of the plant to the tip of the head at intervals of 30, 60 and 90 days after sowing (DAS). The number of pods of 5 randomly selected plants was counted and averaged for different treatments. The yield per plot was calculated by adding the weights of all harvested okra in the respective plot using a weighing machine and was expressed in kilogram (kg). The irrigation water use efficiency (IWUE) and fertilizer use efficiency (FUE) were determined. IWUE, which represents the relation between yield and irrigation water used under different treatments, was calculated as okra yield per hectare per amount of water used.

$$\text{IWUE}\ (\text{kg}\cdot\text{m}^{-3}) = \frac{\text{Weight of okra}\ (\text{kg}\cdot\text{ha}^{-1})}{\text{Amount of water applied}\ (\text{m}^{3}\cdot\text{ha}^{-1})} \qquad (5)$$

FUE, which represents the relation between yield and amount of fertilizer applied was calculated in term of okra yield per hectare per amount of fertilizer applied.

$$\text{FUE}\ (\text{kg}\cdot\text{kg}^{-1}) = \frac{\text{Weight of okra}\ (\text{kg}\cdot\text{ha}^{-1})}{\text{Amount of fertilizer applied}\ (\text{kg}\cdot\text{ha}^{-1})} \qquad (6)$$

Analysis of results

The Surfer software was used to draw the soil water dynamics map in the study area. The results were statistically analysed using two-factor split-plot design in the OP stat software (Sheoran, 2010) to test their significance at 5%. The critical difference (C.D.) at 5% level of probability was computed to check the significance of results.

RESULTS AND DISCUSSION

Amount of water used under different treatments

Table 4 shows the observed discharge rate ($L\cdot h^{-1}$) per can in the drip irrigation system at the experimental site. The observed average dripper discharge was 2.24 $L\cdot h^{-1}$ and 2.06 $L\cdot h^{-1}$ during 2019-20 and 2020-21, respectively. The calculated emission uniformity of the system was 90%. The irrigation time was calculated based on the drip discharge and the volume of water applied. Table 5 shows the maximum temperature (T_{max}), minimum temperature (T_{min}), pan evaporation (ET_{pan}), rainfall and volume of water applied during the years of the experiment. The rainfall received during the cropping periods of 2019–20 and 2020–21 was 68 and 79 mm. The effective rainfall measured was used to calculate the irrigation water requirement. The total amount of water applied per plot during the entire period of the experiment was 317 and 358 L (Table 5) in the years 2019–20 and 2020–21, respectively. The same amount of water was applied in each treatment during both seasons. During the first experimental year (i.e. 2019), the highest amount of water applied was 12.79 L per plot, on 10 August 2019. The total amount of irrigation water applied was 317 L per plot during the cropping season, which in terms of depth was 35.31 cm. The total number of rainy days during the cropping season was 19, which received 68 mm of monthly average rainfall. During the year 2020, the maximum amount of water applied in a day was 14.39 $L\cdot plot^{-1}$, on 7 August 2020. The total amount of irrigation water applied was 356.37 $L\cdot plot^{-1}$ during the cropping season, which in terms of depth was 40.86 cm. The total number of rainy days during the cropping season was 24, which received 79 mm of monthly average rainfall.

Spatio-temporal movement of soil moisture under different lateral spacing and irrigation frequency

Tables 6 and 7 show the moisture variation at 45 and 60 cm lateral spacing, respectively, at radial (0, 11.25 and 22.5 cm) and vertical (0–15, 15–30, 30–45, 45–60 cm) distance under different irrigation frequencies at 30, 60 and 90 DAS during both seasons. At 45 cm lateral spacing (Table 6), during the cropping period of 30 DAS to 90 DAS, the moisture content in the root zone for daily irrigation, just below the dripper (at 0 cm radial distance), ranged from 14.31–15.06%, 14.03–14.56%, 11.75–12.40% and 11.16–11.85% for root zone depth of 0–15 cm, 15–30 cm, 30–45 cm and 45–60 cm, respectively. For a radial distance of 11.25 cm, moisture content varied from 13.09–13.76%, 13.20–13.91%, 11.35–12.05% and 10.98–11.54% for root zone depth of 0–15 cm, 15–30 cm, 30–45 cm and 45–60 cm, respectively. Further, at a radial distance of 22.5 cm, moisture content ranged from 11.71–13.32%, 11.45–12.60%, 10.41–10.84% and 9.87–10.34% at root zone depth of 0–15 cm, 15–30 cm, 30–45 cm and 45–60 cm, respectively. It was found from the results that across the different irrigation frequencies, the average moisture content at radial distance of 0 cm from the dripper (i.e., below the dripper or near plant) was highest, followed by 11.25 cm and 22.5 cm radial distance. A similar pattern was observed at 60 cm lateral spacing, (Table 7) which shows the highest moisture content at radial distance of 0 cm followed by 15 cm and 30 cm.

Table 4. The discharge rate ($L\cdot h^{-1}$) per can used in the subsurface drip irrigation system

Study period	Catch can no.										Mean discharge (L/h)
	1	2	3	4	5	6	7	8	9	10	
2019–20	2.56	2.45	2.38	2.36	2.4	2.25	2.15	1.98	1.92	1.9	2.24
2020–21	2.35	2.3	2.25	2.18	2.15	1.98	1.9	1.88	1.82	1.76	2.06

Table 5. Meteorological parameters, and volume of water applied during the years of the experiment

Study period	Months	T_{max} (°C)	T_{min} (°C)	ET_{pan} (mm)	Rainfall (mm)	Volume of water applied per month per plot (L)	Total volume of water applied per season per plot (L)
2019–20	Jun 2019	39	25	30	30	19.37	317
	Jul 2019	34	24	151	120	18.58	
	Aug 2019	35	26	136	96	170.89	
	Sep 2019	22	15	104	28	108.05	
2020–21	Jun 2020	39	28	106	43	47.70	356
	Jul 2020	32	20	189	173	119.63	
	Aug 2020	31	24	144	62	149.33	
	Sep 2020	23	17	87	40	39.74	

Table 6. Observed moisture content (%) at 30, 60 and 90 DAS at 45 cm lateral spacing in the year 2020

Treatments	Depth (cm)	30 DAS			60 DAS			90 DAS		
		Radial distance (cm)			Radial distance (cm)			Radial distance (cm)		
		0	11.25	22.5	0	11.25	22.5	0	11.25	22.5
$L_{45}I_1$	0–15	15.06	13.76	13.32	14.74	13.45	12.08	14.31	13.09	11.71
	15–30	14.56	13.45	12.60	14.48	13.91	12.34	14.03	13.20	11.45
	30–45	12.40	12.05	10.84	12.15	11.35	10.65	11.75	11.45	10.41
	45–60	11.85	11.54	10.34	11.56	11.12	10.14	11.16	10.98	9.87
$L_{45}I_2$	0–15	14.53	13.33	11.29	14.22	13.06	11.06	13.79	12.64	10.73
	15–30	14.29	13.04	11.70	13.95	12.87	11.45	13.05	12.53	11.12
	30–45	12.92	11.79	10.52	12.63	11.64	10.31	12.23	11.23	9.98
	45–60	13.28	12.15	10.78	13.12	11.93	10.54	12.60	11.57	10.25
$L_{45}I_3$	0–15	13.62	12.45	11.09	13.27	12.27	10.85	12.94	11.90	10.57
	15–30	13.29	12.17	10.86	13.05	11.96	10.64	12.62	11.62	10.33
	30–45	13.20	12.13	10.76	12.95	11.83	10.55	12.55	11.53	10.24
	45–60	13.65	12.51	11.11	13.34	12.27	10.87	12.96	11.87	10.65
$L_{45}I_4$	0–15	12.72	11.68	10.38	12.47	11.44	10.47	12.09	11.09	10.08
	15–30	12.90	11.82	10.57	12.64	11.57	10.28	12.26	11.22	9.90
	30–45	13.46	12.15	11.18	13.22	12.07	10.75	13.02	11.70	10.44
	45–60	13.87	12.69	11.50	13.62	12.46	11.13	13.26	12.16	10.88

Note: DAS = days after sowing

Table 7. Observed moisture content (%) at 30, 60 and 90 DAS with 60 cm lateral spacing in the year 2020

Treatment	Depth (cm)	30 DAS			60 DAS			90 DAS		
		Radial distance (cm)			Radial distance (cm)			Radial distance (cm)		
		0	15	30	0	15	30	0	15	30
$L_{60}I_1$	0–15	15.04	13.42	11.83	14.72	13.10	11.63	14.30	12.67	11.23
	15–30	14.77	13.12	11.57	14.43	12.78	12.03	14.05	12.35	11.68
	30–45	12.40	10.77	10.28	12.06	10.48	9.43	11.72	10.14	9.42
	45–60	11.78	10.18	9.76	11.45	10.25	9.55	11.15	10.34	9.13
$L_{60}I_2$	0–15	14.41	12.82	11.53	14.16	12.46	11.25	13.78	12.12	10.82
	15–30	14.23	12.91	11.25	13.94	12.06	11.03	13.57	11.88	10.71
	30–45	12.94	11.23	10.04	12.62	10.98	9.65	12.23	10.59	9.57
	45–60	13.18	11.54	10.35	12.76	11.51	10.13	12.62	10.93	9.75
$L_{60}I_3$	0–15	13.58	11.87	10.67	13.26	11.67	10.36	12.84	11.22	9.92
	15–30	13.31	11.63	10.32	13.06	11.39	10.05	12.58	10.98	9.73
	30–45	13.16	11.57	10.18	12.92	11.23	10.02	12.48	10.86	9.68
	45–60	13.67	11.88	10.67	13.34	11.65	10.43	12.94	11.26	10.04
$L_{60}I_4$	0–15	12.68	11.04	9.87	12.42	10.82	9.57	12.06	10.38	9.21
	15–30	12.58	11.15	9.98	12.61	10.95	9.77	12.23	10.56	9.37
	30–45	13.42	11.75	10.45	13.17	11.52	10.34	12.83	11.17	9.84
	45–60	13.81	12.16	10.84	13.58	11.89	10.57	13.21	11.48	10.34

Note: DAS = days after sowing

The moisture content in terms of depth decreased with increase in root zone depth and radial distance (Tables 6 and 7). The highest moisture content was found at 0–15 cm depth below the dripper or near it (0 cm from dripper), for all the lateral spacings at under 30 DAT and a daily irrigation frequency.

Table 8 shows the depth of water available in the entire root zone (0–60 cm) at different lateral spacings (i.e. 45 and 60 cm), irrigation frequencies and radial distances in the year 2020–21. At 45 cm lateral spacing, the depth of water available during the cropping period of 30 to 90 DAS at a 0, 12.5 and 25 cm radial

Table 8. Depth of available water in the entire root zone (0–60 cm) in the year 2020

Treatment	30 DAS			60 DAS			90 DAS		
	Radial distance (cm)			Radial distance (cm)			Radial distance (cm)		
	0	11.25	22.5	0	11.25	22.5	0	11.25	22.5
$L_{45}I_1$	12.61	11.89	11.02	12.39	11.66	10.58	11.99	11.40	10.16
$L_{45}I_2$	12.87	11.77	10.36	12.62	11.58	10.15	12.09	11.22	9.85
$L_{45}I_3$	12.58	11.53	10.25	12.31	11.31	10.04	11.95	10.98	9.78
$L_{45}I_4$	12.39	11.31	10.21	12.16	11.12	9.98	11.85	10.80	9.66
	0	15	30	0	15	30	0	15	30
$L_{60}I_1$	12.63	11.11	10.16	12.32	10.91	9.98	11.99	10.65	9.70
$L_{60}I_2$	12.81	11.35	10.10	12.51	11.00	9.84	12.21	10.65	9.56
$L_{60}I_3$	12.57	10.99	9.79	12.30	10.75	9.56	11.90	10.37	9.21
$L_{60}I_4$	12.28	10.79	9.63	12.12	10.57	9.42	11.78	10.20	9.07

distance ranged from 11.99–12.61 cm, 11.40–11.89 cm and 10.16–11.02 cm, respectively, for daily irrigation, from 12.09–12.87 cm, 11.22–11.77 cm and 9.85–10.36 cm, respectively, for irrigation after 1 day, from 11.95–12.58 cm, 10.98–11.53 cm and 9.78–10.25 cm, respectively, after 2 days, and from 11.85–12.39 cm, 10.80–11.31 cm and 9.66–10.21 cm, respectively, after 3 days. It can be seen from the results that at 45 cm lateral spacing, for 30, 60 and 90 DAT, near-dripper available depth of water was highest, followed by 11.25 cm and 22.5 cm radial distance. The results at 60 cm lateral spacing for 30, 60 and 90 DAT shows a similar pattern. Further, it can be seen from the results that moisture content was high at 45 cm lateral spacing in comparison to 60 cm lateral spacing for all the treatments.

Radial and vertical movement of moisture in the study area

Figures 3–5 show the radial (at 0 cm, 11.25 cm and 22.5 cm) and vertical (at 0 to 60 cm) movement of soil moisture at different irrigation frequencies (daily, after 1 day, 2 days and 3 days) at 45 cm lateral spacing under the cropping period of 30, 60 and 90 days. The soil moisture content was higher near the dripper and decreased with increasing radial distance from the dripper. The vertical distribution of moisture content was observed to be different under different irrigation frequencies.

With daily irrigation, the moisture content decreased with increase in the root zone depth but this decrease in moisture content with root zone depth is less under 1-, 2-, and 3-day irrigation interval. With irrigation after 2 days, the moisture content remained almost constant with depth, but with irrigation after 3 days, moisture content was lower in the top layer than the bottom layer. Overall soil moisture decreased laterally but increased vertically downward with the increase in the irrigation interval (Figs 3–5). In daily irrigation treatment in the root zone, at 30, 60 and 90 DAS, moisture content decreased with increase in depth but this difference reduced with an increase in irrigation interval. A similar pattern was observed for the 1- and 2-day irrigation interval. However, for the 3-day interval, moisture content increases with an increase in depth (Figs 3–5). Overall, soil moisture decreased laterally, but increased vertically downward with the increase in irrigation interval. A similar pattern was observed for radial and vertical movement of moisture at 60 cm lateral spacing under different irrigation frequencies (Figs 6–8). Moisture content was higher at 45 cm lateral spacing in comparison to 60 cm lateral spacing. These results are in agreement with those of Bajpai and Kaushal (2020) for a sandy area.

Contour maps (Figs 9–16) were also prepared using the Surfer software (2014) to show the soil moisture distribution pattern at 30, 60 and 90 DAS under various irrigation frequencies and lateral spacings. It can be seen from figures that the moisture variation in the root zone is also a function of irrigation frequency and lateral spacing. High moisture content occurs under closer lateral spacing and more frequent irrigation. Badr and Abuarab (2013) also concluded that irrigation water distribution efficiency is higher for closer lateral spacing than wider lateral spacing. Further, it was also observed that during more frequent irrigation higher moisture content was maintained in the top layer of the root zone which is readily available to the plant, whereas for longer irrigation intervals, moisture content in the lower layer of the root zone remained higher than in the top layer, resulting in less water being available to the plant.

Regarding crop growth stages, moisture content decreases with an increase in crop growth period (i.e., high at 30 DAS and lower at 90 DAS) for the same frequency, depth and radial distance, due to plant uptake of water. The results also show that with an increase in the irrigation interval from daily to 1, 2, and 3 days, the water availability to the plants was reduced accordingly, even though the total amount of water applied in all treatments was equal. This is due to the sandy loam soil in the experimental plots in which more downward flow of water occurs with an increase in irrigation interval and with the amount of irrigation water per irrigation increased. In daily irrigation, less water was applied per irrigation which causes the retention of more moisture content in the top layer with minimum percolation losses, whereas during irrigation after 3 days, more water was applied per irrigation and lower moisture content was observed in the top layer in comparison to the lower layer due to greater percolation losses from the top to lower layers. Under daily irrigation, moisture content was higher in the upper layer of the root zone from which a plant extracts the most water, whereas moisture content decreased relatively with the increase in irrigation interval. But in lower layers moisture content was lowest for the daily irrigation treatment and increased relatively with the increase in irrigation interval, i.e., after 1, 2 and 3 days. Wan and Kang (2006) also observed that with a decrease in irrigation frequency, the dry domain became larger within the whole root zone. Kumari et al. (2018) also predicted the optimum moisture content under a once-in-2-days irrigation frequency to be 80% of ET_c, based on maximum yield.

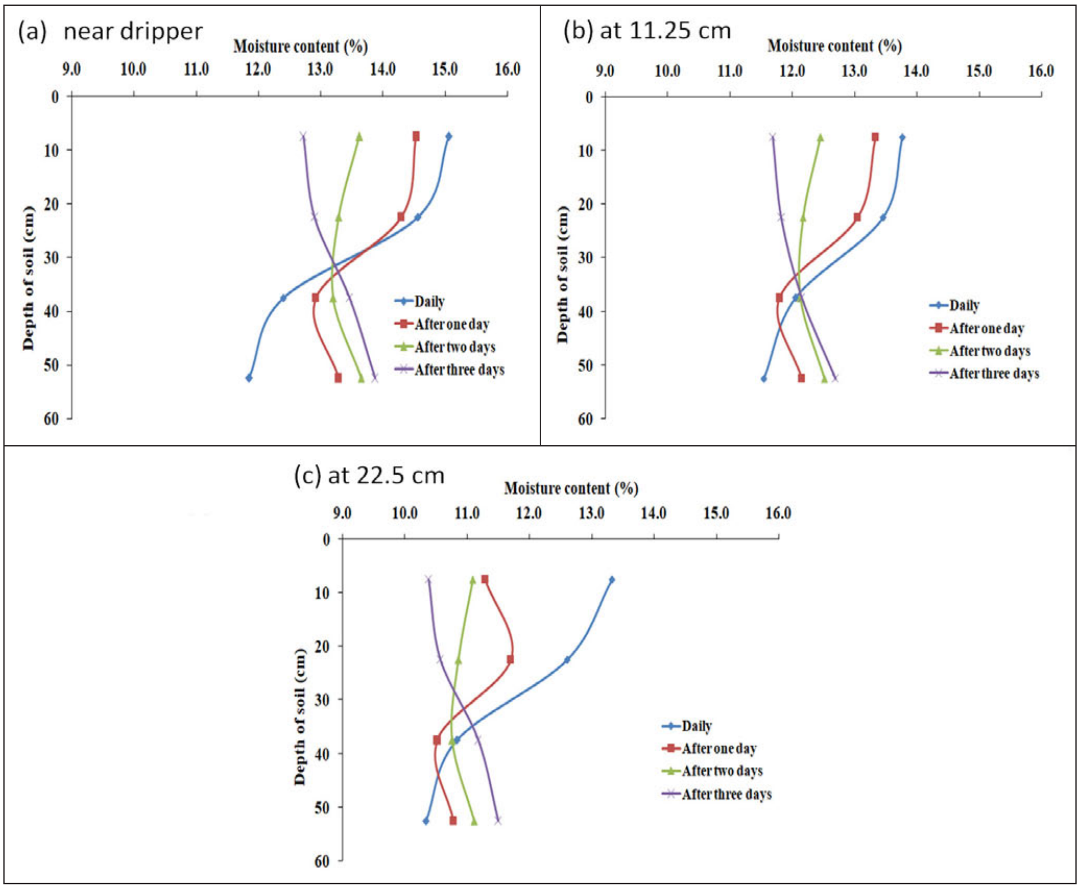

Figure 3. Radial and vertical movement of moisture in the root zone at 30 DAS at 45 cm lateral spacing: (a) near dripper, (b) at 11.25 cm, and (c) at 22.50 cm

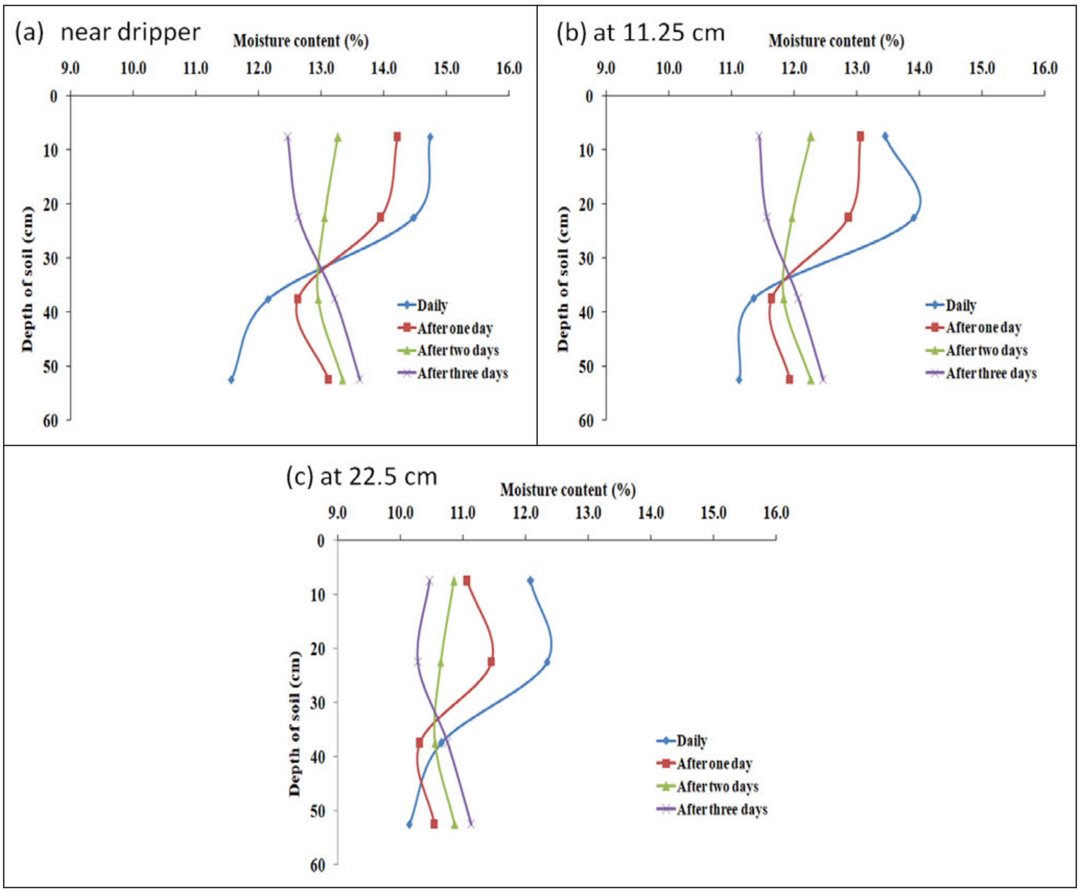

Figure 4. Radial and vertical movement of moisture in the root zone at 60 DAS at 45 cm lateral spacing: (a) near dripper, (b) at 11.25 cm, and (c) at 22.50 cm

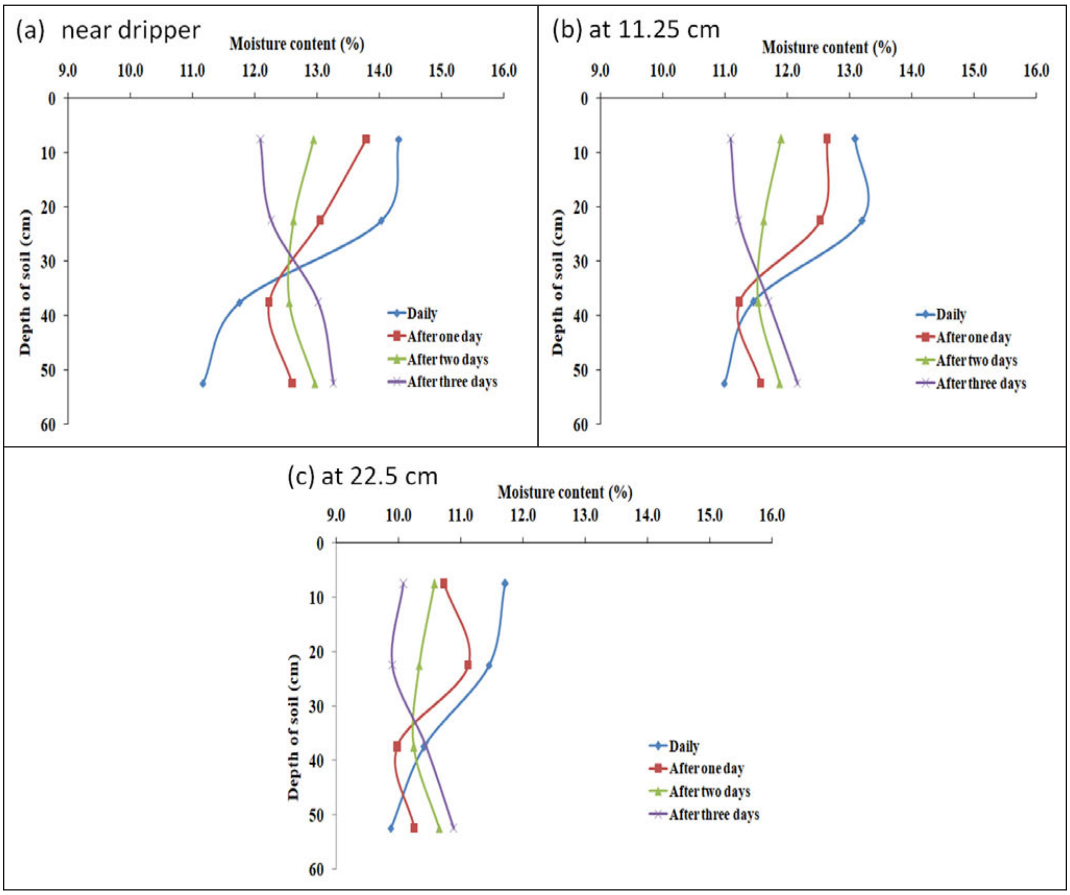

Figure 5. Radial and vertical movement of moisture in the root zone at 90 DAS at 45 cm lateral spacing: (a) near dripper, (b) at 11.25 cm, and (c) at 22.50 cm

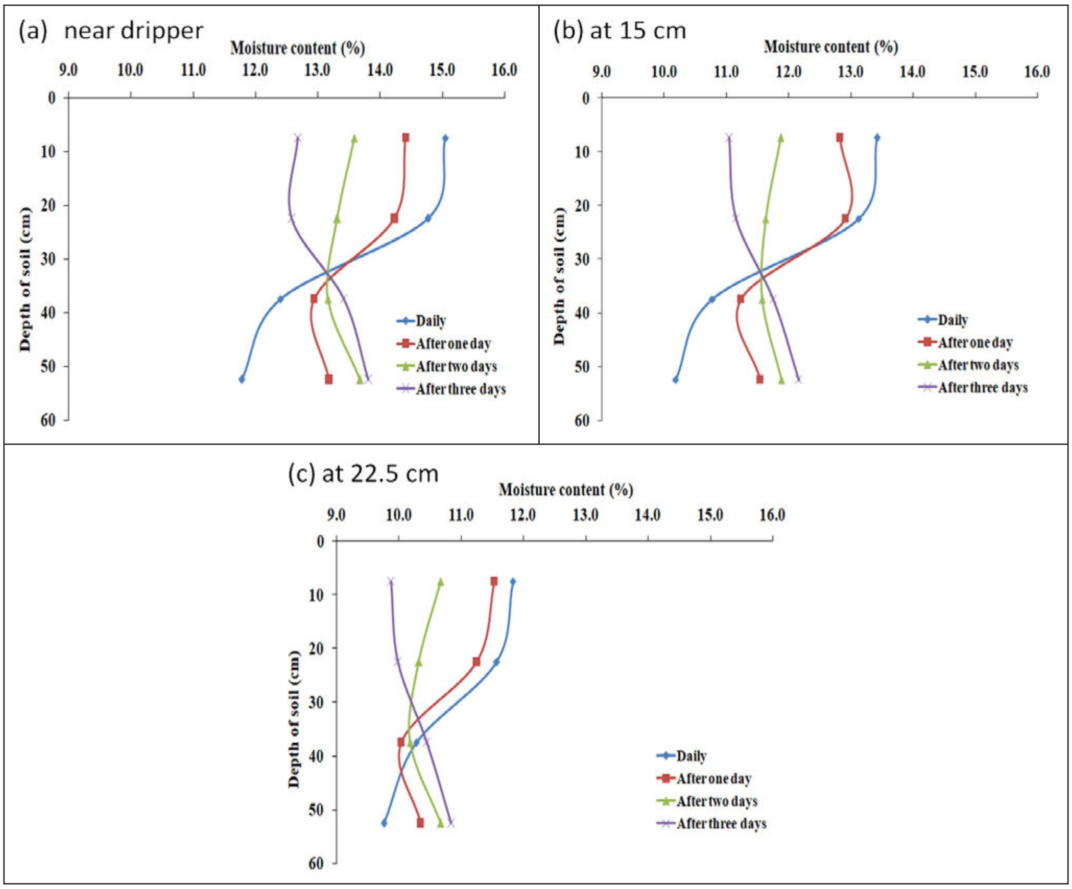

Figure 6. Radial and vertical movement of moisture in the root zone at 30 DAS at 60 cm lateral spacing: (a) near dripper, (b) at 15 cm, and (c) at 22.50 cm

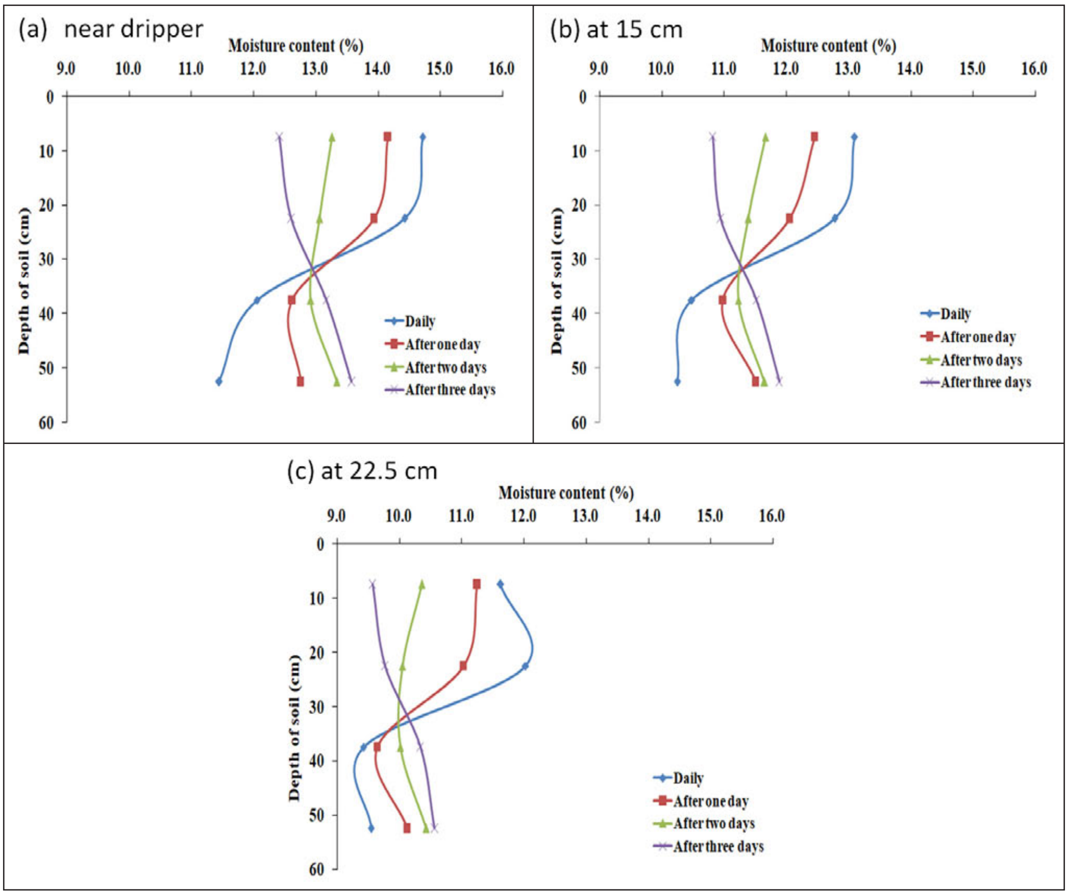

Figure 7. Radial and vertical movement of moisture in the root zone at 60 DAS at 60 cm lateral spacing: (a) near dripper, (b) at 15 cm, and (c) at 22.50 cm

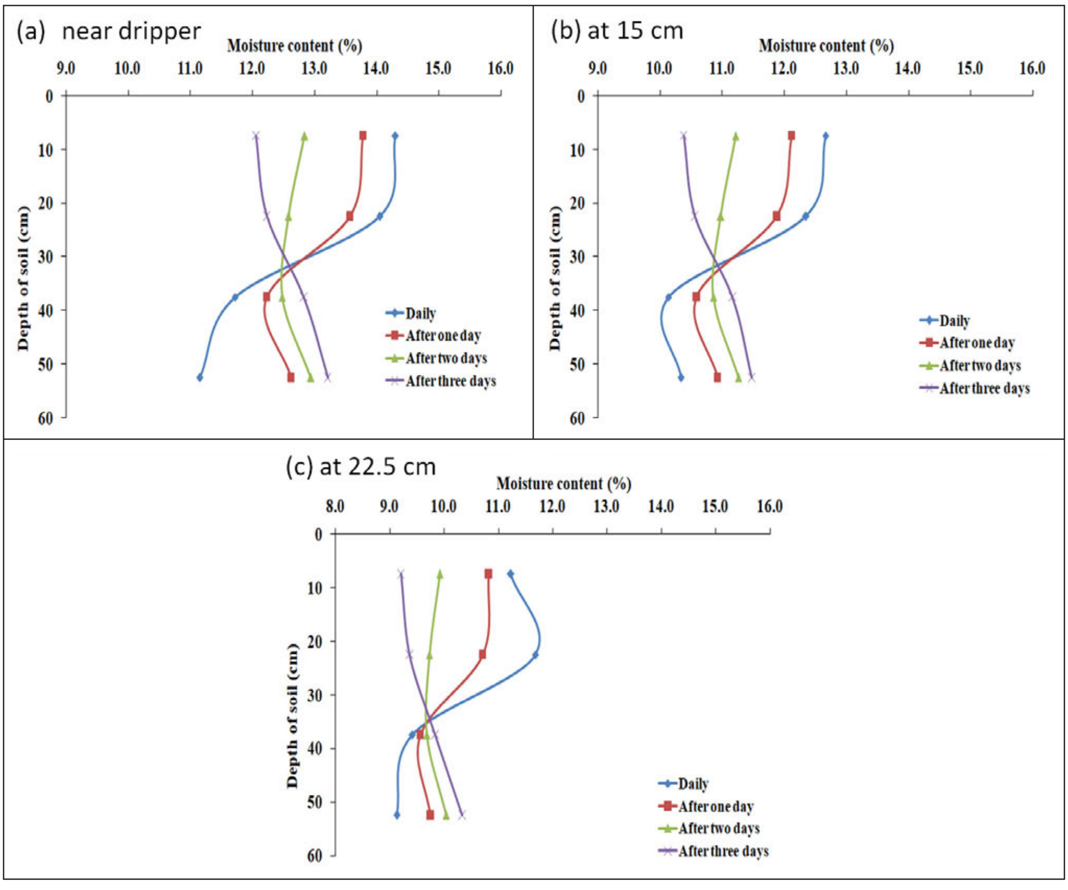

Figure 8. Radial and vertical movement of moisture in the root zone at 90 DAS at 60 cm lateral spacing (a) near dripper, (b) at 15 cm, and (c) at 22.50 cm

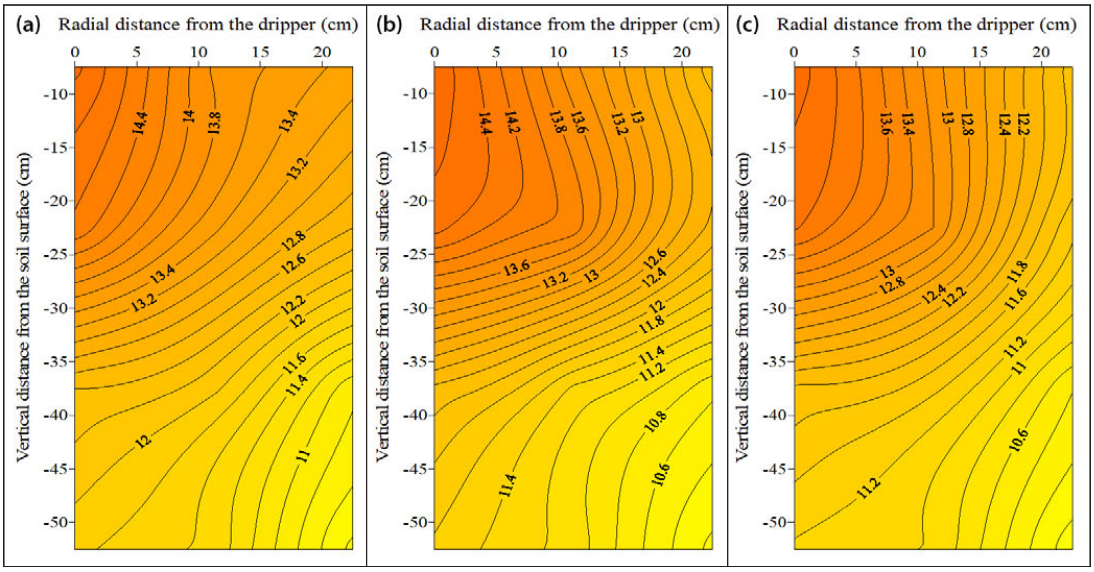

Figure 9. Moisture content contour map at daily irrigation frequency under (a) 30, (b) 60 and (c) 90 DAS at 45 cm lateral spacing

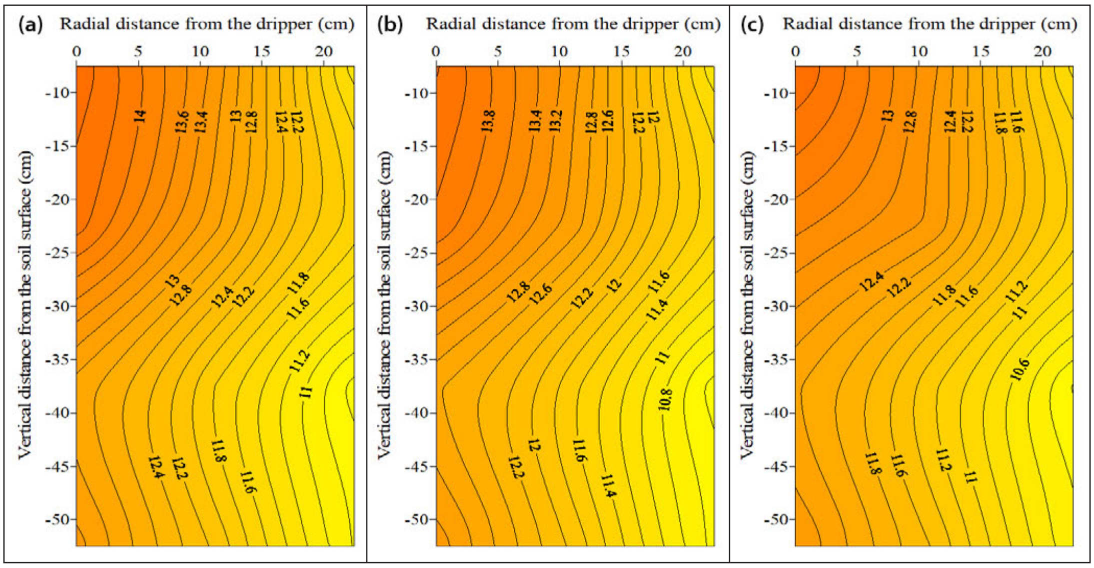

Figure 10. Moisture content contour map at alternate day irrigation frequency under (a) 30, (b) 60 and (c) 90 DAS at 45 cm lateral spacing

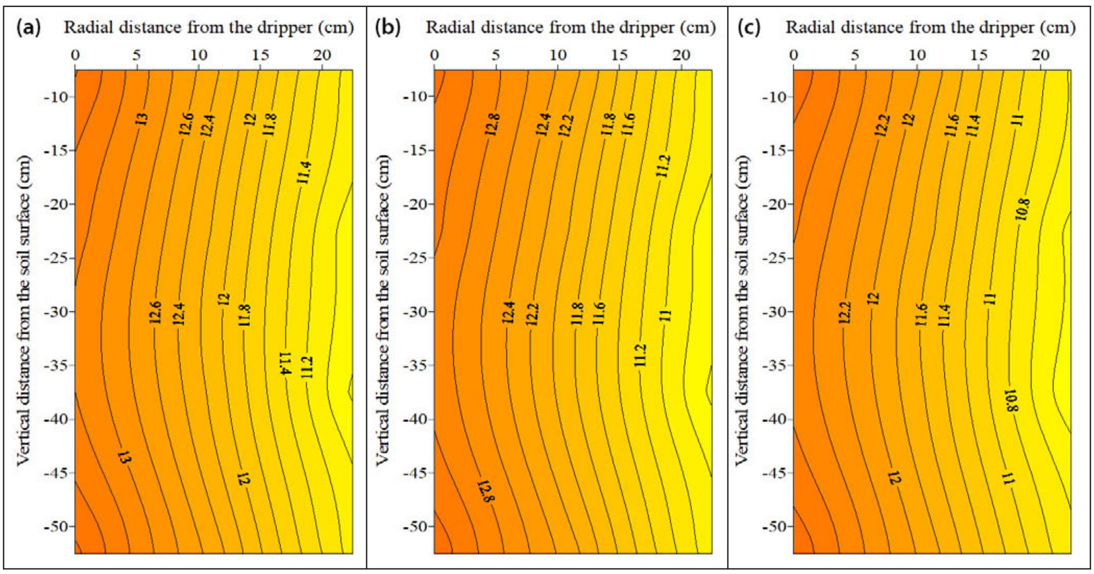

Figure 11. Moisture content contour map with after-2-day irrigation frequency under (a) 30, (b) 60 and (c) 90 DAS at 45 cm lateral spacing

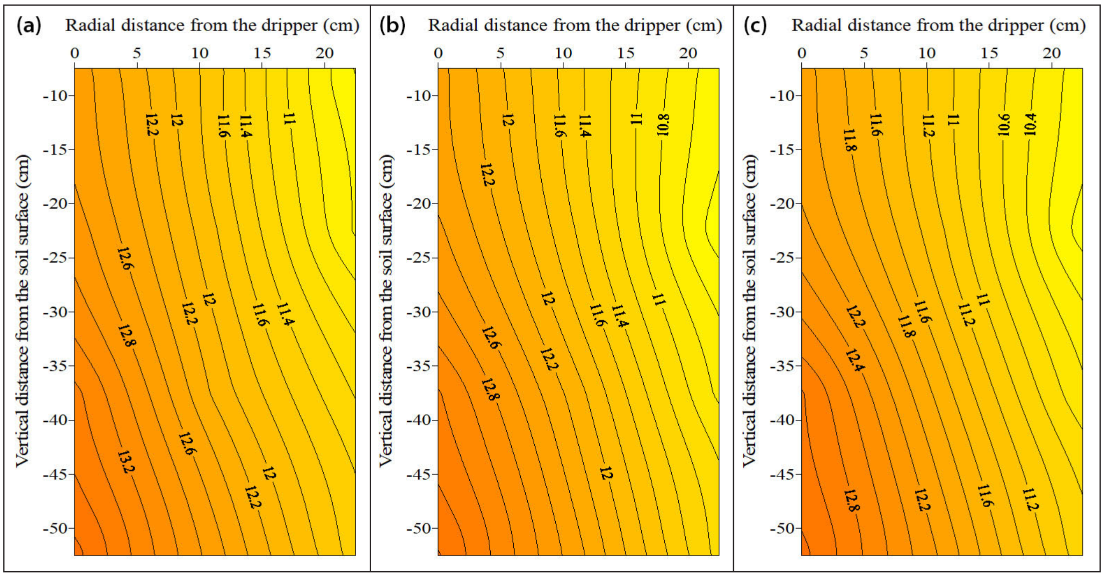

Figure 12. Moisture content contour map with after-3-day irrigation frequency under (a) 30, (b) 60 and (c) 90 DAS at 45 cm lateral spacing

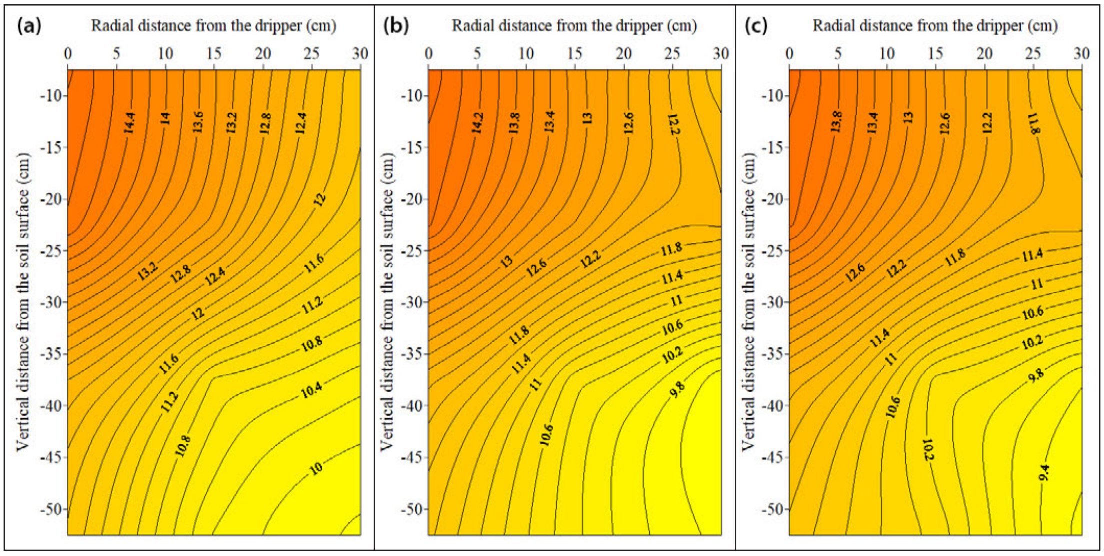

Figure 13. Moisture content contour map at daily irrigation frequency under (a) 30, (b) 60 and (c) 90 DAS at 60 cm lateral spacing

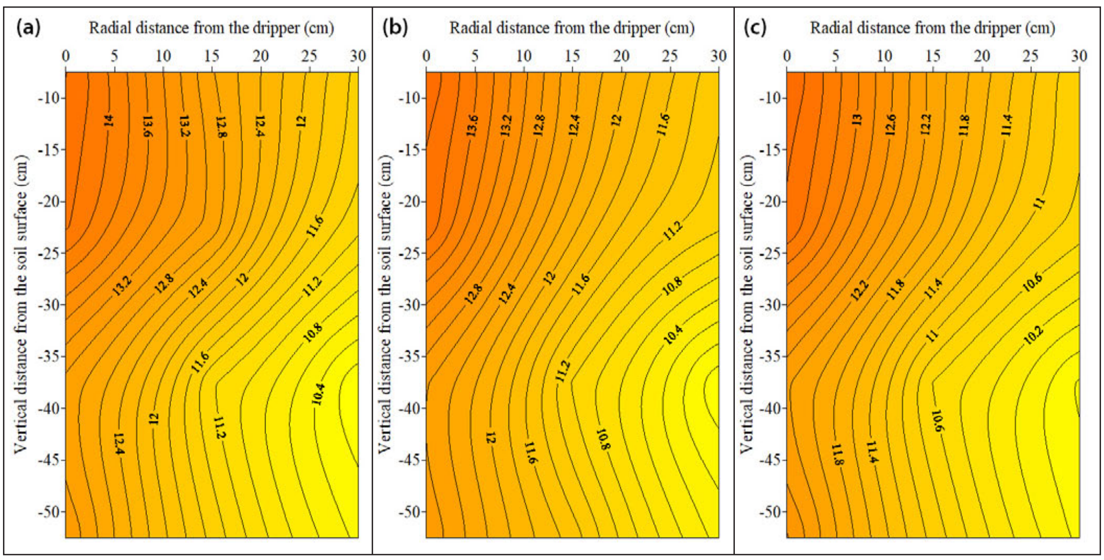

Figure 14. Moisture content contour map at alternate day irrigation frequency under (a) 30, (b) 60 and (c) 90 DAS at 60 cm lateral spacing

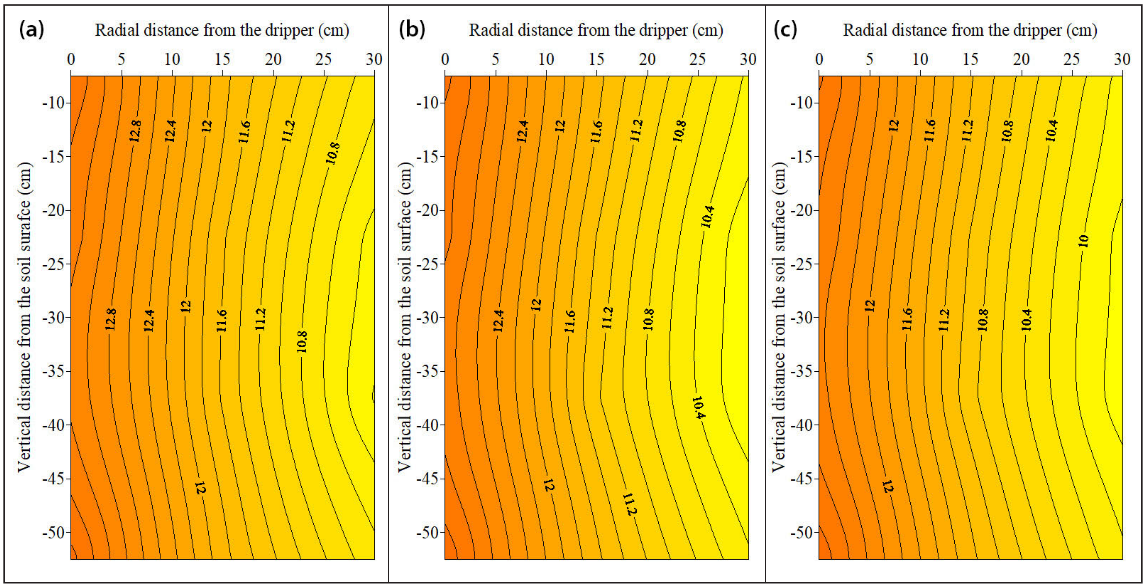

Figure 15. Moisture content contour map with after-2-day irrigation frequency under (a) 30, (b) 60 and (c) 90 DAS at 60 cm lateral spacing

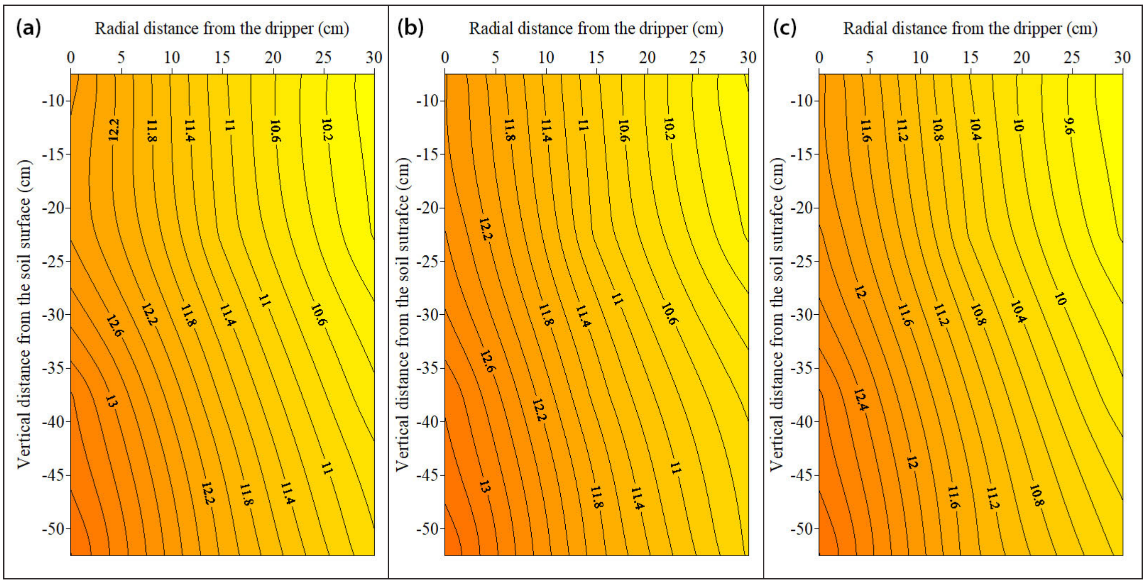

Figure 16. Moisture content contour map with after-3-day irrigation frequency under (a) 30, (b) 60 and (c) 90 DAS at 60 cm lateral spacing

Yield and growth parameters under different irrigation frequencies and lateral spacings

Table 9 shows the measured growth parameters and yield of okra under different treatments during the study period. The results of an ANOVA for 3 replicates of 8 treatments at the 5% significance level showed that treatment I_1 was significantly different from all other treatments in respect of plant height, plant spread, yield, marketable yield, IWUE and FUE, during both 2019 and 2020. Irrigation frequency thus had a significant effect on plant growth and plant height.

At 45 cm lateral spacing, plant height varied from 107 (I_3) to 117.41 (I_1) cm and 102.7 (I_3) to 112.6 (I_1) cm during 2019 and 2020, respectively, and ranged from 94.9 (I_4) to 102.2 cm (I_1) and 90.2 (I_4) to 98.1 (I_2) cm during 2019 and 2020, respectively, at 60 cm lateral spacing. The results indicate that the maximum plant height was obtained with daily irrigation and 45 cm lateral spacing. The response of plant height to different irrigation frequencies under subsurface drip irrigation was significant (Table 9). The results are also in agreement with Abdulrazzak et al. (2020) who reported that plant height of okra under subsurface drip irrigation was greater with daily irrigation.

The pods per plant ranged from 20.3 (I_4) to 23.7 (I_1) and 21 (I_4) to 22.7 (I_1) for 2019 and 2020, respectively, at 45 cm lateral spacing. For 60 cm lateral spacing, this varied from 19.7 (I_4) to 21.7 (I_1) and 19.4 (I_4) to 21.7 (I_2) during 2019 and 2020, respectively. It can be seen from Table 9 that with frequent irrigation (daily and after 1 day) treatments, the number of pods per plants was higher than with the 2- and 3-day irrigation intervals (Table 9.). It was also reported that with a lower irrigation frequency of okra plants, the average number of pods decreased (Radder et al., 2008; Anant et al., 2009).

The maximum yield of okra was obtained with I_1 (11 340 and 11 090 kg·ha^{-1}) for 45 cm lateral spacing and I_1 (10 760 to 10 570 kg·ha^{-1}) for 60 cm lateral spacing. Minimum yield was obtained with I_4 for 45 and 60 cm lateral spacing. The total yield of okra with daily irrigation was higher by 2.39, 7.45 and 13.55%

Table 9. Growth parameters, efficiency and yield of okra under different treatments

Treatments	Plant height (cm)		Pods per plant		Yield ($kg \cdot ha^{-1}$)		IWUE ($kg \cdot m^{-3}$)		FUE ($kg \cdot kg^{-1}$)	
	2019	2020	2019	2020	2019	2020	2019	2020	2019	2020
I_1L_{45}	117.4	112.6	23.7	22.7	11 340	11 090	14.31	12.45	70.9	69.3
I_2L_{45}	113.1	108.6	22.3	22.0	10 940	10 730	13.81	12.04	68.4	67.0
I_3L_{45}	107.0	102.7	21.7	21.3	10 320	10 150	13.02	11.40	64.5	63.5
I_4L_{45}	109.3	104.9	20.3	21.0	9 730	9 580	12.28	10.76	60.8	59.9
I_1L_{60}	100.3	96.3	21.3	21.3	10 760	10 570	13.58	11.86	67.2	66.0
I_2L_{60}	102.2	98.1	21.7	21.7	10 600	10 440	13.37	11.72	66.2	65.2
I_3L_{60}	95.7	92.3	19.7	20.7	10 060	9 970	12.70	11.19	62.9	62.3
I_4L_{60}	94.9	90.2	19.7	20.3	9 290	9 230	11.73	10.36	58.1	57.7
CD at 5%	2.7	3.5	N/A	N/A	2.0	1.9	0.25	0.22	1.2	1.2

than after a 1-, 2- and 3-day irrigation interval, respectively. Haris et al. (2014) also supported the conclusion that daily irrigation is optimal for okra production.

Table 9 also shows the influence of lateral spacing and irrigation frequency on irrigation water use efficiency (IWUE). An equal amount of water was applied in all treatments; therefore, IWUE varies according to variation in total yield, i.e., with an increase in total yield, there is a corresponding increase in IWUE. The highest IWUE (14.31 $kg \cdot m^{-3}$) was obtained with daily irrigation (I_1) and the lowest (10.76 $kg \cdot m^{-3}$) with after-3-days (I_4) irrigation at 45 cm lateral spacing, while for 60 cm lateral spacing, the highest IWUE (13.58 $kg \cdot m^{-3}$) was observed with the I_1 treatment and the lowest (10.76 $kg \cdot m^{-3}$) was found with the I_4 treatment. Lateral spacing of 45 cm showed a higher IWUE during both years of the experiment. Similar results were also reported by Jeelani et al. (2017) for the wet temperate zone of Himachal Pradesh, India. Under daily irrigation frequency, higher yield was observed, which led to higher IWUE in comparison to other irrigation treatments. With a daily irrigation frequency, IWUE was higher than with a 1-, 2- and 3-day irrigation interval.

Under both lateral spacings with daily irrigation frequency, FUE was higher than after 1, 2 and 3 days (Table 9). An equal amount of fertilizer was applied for all treatments; hence FUE varies according to variation in total yield, i.e., with increases in total yield, there is a corresponding increase in FUE. This reflects that a daily irrigation frequency is optimal for obtaining maximum yield, IWUE and FUE, of okra grown in sandy loam soil of Haryana, India. This is likely due to the fact that a daily irrigation frequency maintains the soil moisture at field capacity in the root zone for the okra crop, whereas at lower irrigation frequencies, water moves down to lower layers of the soil profile.

Plant height, numbers of pods per plant, yield, IWUE and FUE were all observed to be maximal at 45 cm as compared to 60 cm lateral spacing (Table 9). The reason for this may be that at 45 cm lateral spacing, plants were grown at 45 cm row-to-row and 40 cm plant-to-plant spacing, which means that plants were very close to drippers, whereas at 60 cm lateral spacing, plants were grown at 60 cm row-to-row and 30 cm plant-to-plant spacing; thus each plant row was not very close to drippers, and got a little less water in comparison to plants with 45 cm lateral spacing, resulting in reduced cell division and hence plant growth was stunted. The other reason may be due to the different plant spacings used, which resulted in a different number of plants per experimental unit. Therefore, variation in yield and other measured parameters may be due to lateral spacing, irrigation frequency and number of plants per unit area. Overall it may be concluded that daily irrigation with 45 cm lateral spacing is the best choice to obtain the maximum yield of okra grown in sandy loam soil, and thereby to increase the income of okra growers/farmers.

CONCLUSIONS

In this study, irrigation scheduling (i.e. timing and amount of water applied), plant growth parameters (i.e. plant height, pods per plant), efficiency (IWUE, FUE) and yield of okra under different lateral spacings (45 cm and 60 cm) and irrigation frequencies (daily and after 1, 2 and 3 days) were assessed in the Kharif season of 2019–20 and 2020–21 in sandy loam soil of Haryana (India). The overall results from the study show that the soil moisture decreased laterally, but increased vertically downward with increase in irrigation interval. Further, on the basis of soil water dynamics, efficiency and yield of okra, it may be concluded that daily irrigation with 45 cm lateral spacing is the best choice to obtain maximum yield and growth among a lateral spacing of either 45 or 60 cm and 4 irrigation frequencies in the semi-arid region of India. This study provides a guideline to increase the income of okra growers/farmers under subsurface drip irrigation in a semi-arid region by choosing the optimal frequency and lateral spacing.

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